# ILC MAIN LINAC SIMULATION

**KIRTI RANJAN**, on behalf of FERMILAB's ILC Main Linac Simulation Group

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- Single-bunch EMITTANCE PRESERVATION in ILC Main Linac
- Main Linac LATTICE Design
- Development of Low Emittance Transport (LET) Study Tools
- Wakefield calculations, Cross-checking codes etc.

## 1. EMITTANCE PRESERVATION

- ILC Main linac will accelerate $e^-/e^+$ from ~5 GeV→ 250 GeV
  - Upgradeable to 500 GeV
- Two MAJOR design issues:


⇨ **ENERGY :** Efficient acceleration of the beams

⇨ **LUMINOSITY :** Emittance preservation

Luminosity Scaling

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{CM}} \sqrt{\frac{\delta_{BS}}{\varepsilon_y}} H_D$$

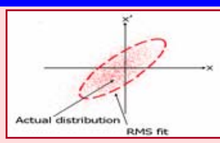
⇨ SMALL Normalized Vertical emittance

⇨ *Vertical plane* - more challenging:

- ⇨ Large aspect ratio (x:y) in both spot size & emittance (400:1)
- ⇨ ~ 2-3 orders of magnitude more difficult

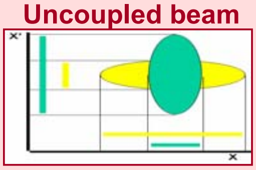
## WHAT IS EMITTANCE ?

- ~ Beam size * Divergence
- Phase space area occupied by the beam
- Normalized emittance is invariant in Conservative system

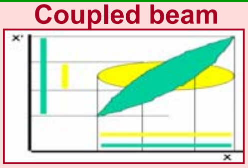



*particles distributed in Phase space*

Uncoupled beam



Coupled beam



EMITTANCE DILUTION – In the presence of beam coupling, the product of the projections of the phase space area on the X and X' axes is a NOT a constant

## SOURCES OF EMITTANCE DILUTION

### Single Bunch

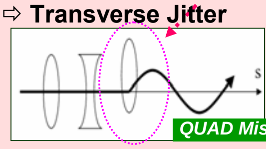
⇨ Transverse Wakefields:

- ⇨ Short Range : Misaligned cavities or cryomodules

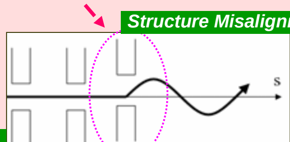
⇨ Dispersion from Misaligned Quads or Pitched cavities

⇨ XY-coupling from rotated Quads

⇨ Transverse Jitter



*QUAD Misalignment*



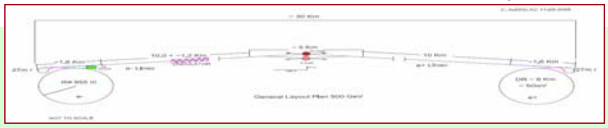
*Structure Misalignment*

### Nominal Installation Tolerances of components

| Tolerance | Vertical (y) plane |
|---|---|
| BPM Offset w.r.t. Cryostat | 300 μm |
| Quad offset w.r.t. Cryostat | 300 μm |
| Quad Rotation w.r.t. Cryostat | 300 μrad |
| Cavity Offset w.r.t. Cryostat | 300 μm |
| Cryostat Offset w.r.t. Survey Line | 200 μm |
| Cavity Pitch w.r.t. Cryostat | 300 μrad |
| Cryostat Pitch w.r.t. Survey Line | 20 μrad |
| BPM Resolution | 1.0 μm |

## Baseline Configuration Document (BCD)

*"The baseline configuration document (BCD) is a snapshot of what we can understand and defend at this time."* Barry Barish



- **TUNNEL -** "Until on-going beam dynamics simulations show otherwise, the *linac will follow the curvature of the earth*, unless a site-specific reason (cost driven) dictates otherwise."
- **CAVITY -** *"31.5 MV/m gradient and Q of 1×10^10* would be achieved on average in a linac made with *eight-cavity CM*"
- **LATTICE –** *"Every 4th CM* in the linac would include a cos(2*phi)-type *quadrupole* that also would contain horizontal and vertical corrector windings (this corresponds to a *constant beta lattice with one quadrupole every 32 cavities*)."

- Cryogenic system is divided into CryoModules (CM) with 8 RF cavities/ CM
- Magnet Optics : FODO lattice, with β phase advance of $75^0$ / $60^0$ in x /y plane
- Each quad has a *BPM & Vertical Corrector* magnet.

### MAIN LINAC DESIGN

- ⇨ 10.5 km length
- ⇨ 9 Cell structures at 1.3 GHz
- ⇨ Gradient: 31.5 MeV/m
- ⇨ Injection energy = 15.0 GeV
- ⇨ Initial Energy spread= 150 MeV

### BEAM CONDITIONS

- ⇨ Bunch Charge: $2.0 \times 10^{10}$ particles/bunch
- ⇨ Bunch length = 300 μm
- ⇨ Normalized injection y-emittance = 20 nm-rad

## BEAM BASED ALIGNMENT

- Alignment tolerances can not be met by *ab initio* installation – need beam-based measurements
- "Beam Based Alignments (BBA)": techniques which provide information on beamline elements using measurements with the beam
  - ⇨ "One-to-One" (1:1) Correction; Dispersion Free Steering; Dispersion bumps, Ballistic Alignment, etc.

### *One-to-One (1:1) Steering*

- Find a set of BPM Readings for which beam should pass through the exact center of every quad
- Use the correctors to Steer the beam

One-to-One alignment generates *dispersion* which contributes to emittance dilution and is sensitive to the BPM-to-Quad offsets

### *DISPERSION FREE STEERING (DFS):*

DFS is a technique that aims to directly measure and correct dispersion in beamline

- Measure dispersion (via mismatching the beam energy to the lattice)
- Calculate correction (via steering magnets) needed to zero dispersion apply the correction

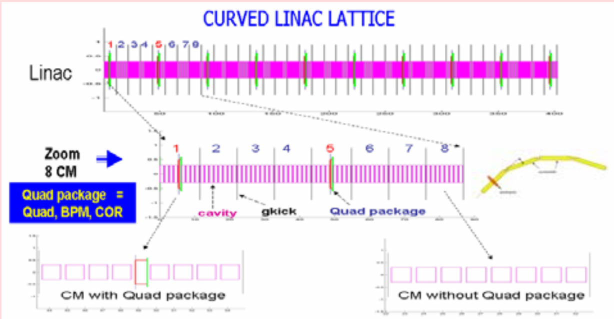
⇨Successful in rings (LEP, PEP ) but less successful at SLC (Two-beam DFS achieved better results) (Note: SLC varied magnet strengths (center motion?))

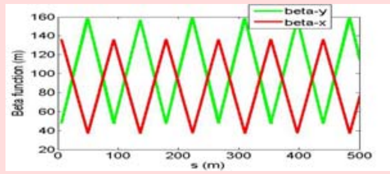
# SIMULATION USING MAT-LIAR (LInear Accelerator Research Code)

⇨Tool to study beam dynamics, simulate regions with accelerator structures & includes wakefield & dispersive emittance dilution

⇨ Includes diagnostic and correction devices, including BPMs, dipole correctors, beam-based feedbacks etc

➢ MATLAB drives the whole package allowing fast development of correction




| | |
|---|---|
| Length (m) : | 10.4km |
| N_quad : | 240 |
| N_cavity : | 7680 |
| N_bpms : | 241 |
| N_Xcor : | 240 |
| N_Ycor : | 241 |
| N_gkicks : | 1920 |

➢ Modifications in LIAR @FNAL to simulate the curvature:

- The curvature is simulated by adding kinks between the cryomodules
- The matched dispersion condition at the beginning of the linac can now be artificially introduced into the initial beam

## ONE-TO-ONE STEERING

➢ Divide linac into segments of~50 quads/segment

➢ Read all Q-BPMs in a single pulse

➢ Compute set of corrector readings and apply the correction

⇨ Constraint – minimize RMS of the BPM readings

➢ Iterate few times before going to the next segment

➢ Performed for 50 Seeds

## DISPERSION FREE STEERING (DFS)

➢ Divide linac into segments of ~40quads

➢ Two orbits are measured

➢ Vary energy by switching off cavities in front of a region

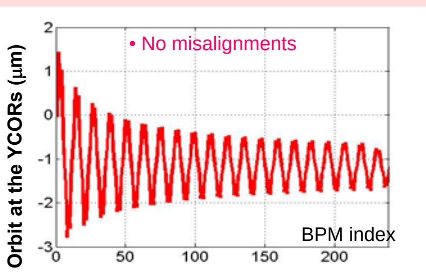
➢ Measure change in orbit & apply correction

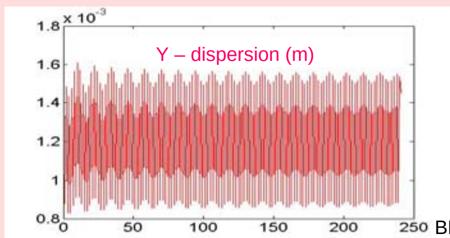
⇨ Constraint - simultaneously minimize dispersion and RMS of the BPM readings

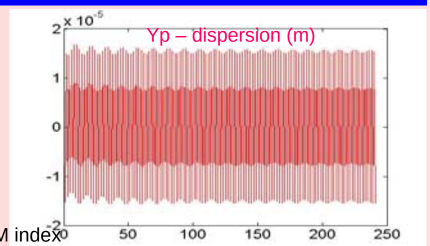
➢ Iterate twice before going to the next segment

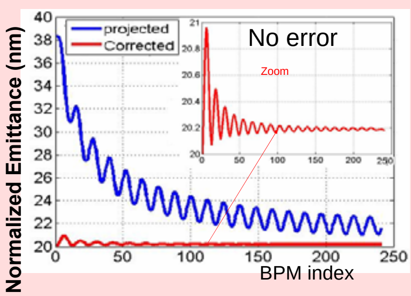
➢ Performed for 50 Seeds

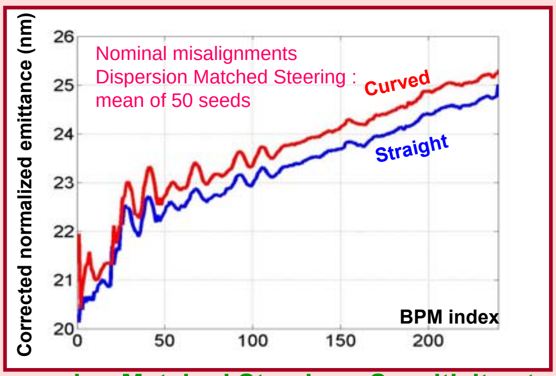
# RESULTS



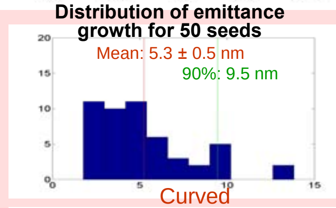



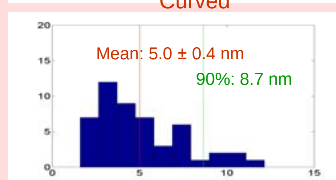



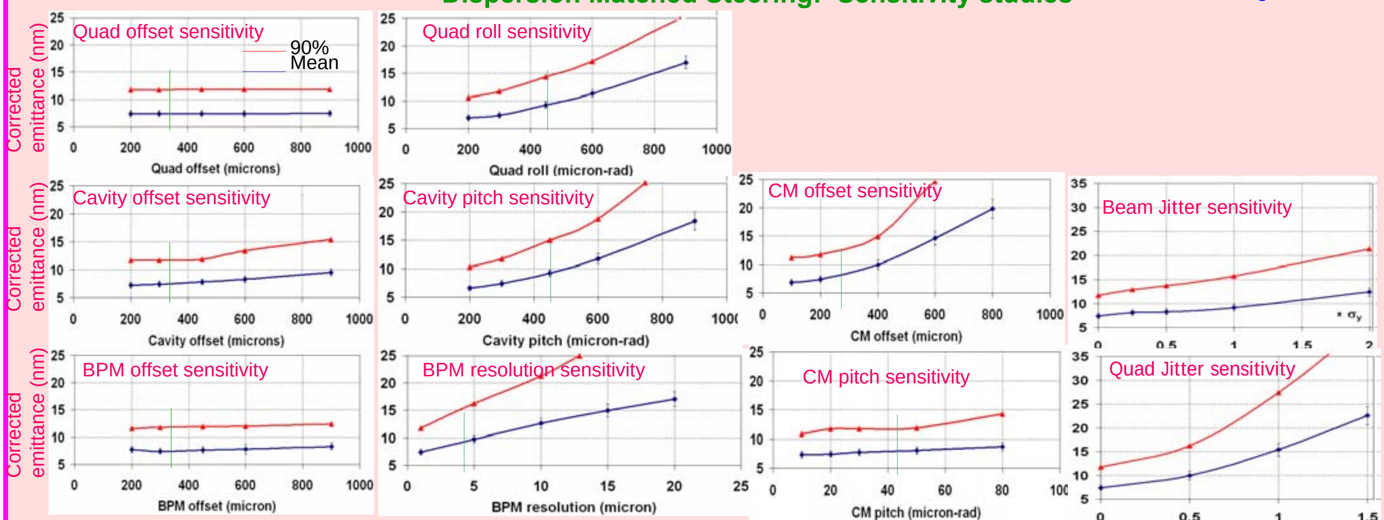

Distribution of emittance growth for 50 seeds



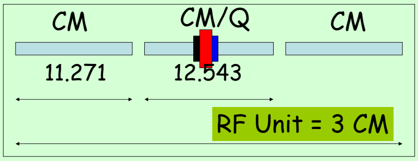

Laser Straight

## Dispersion Matched Steering: Sensitivity studies

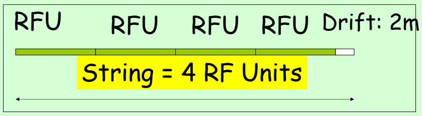


# 2. LINAC LATTICE DESIGN

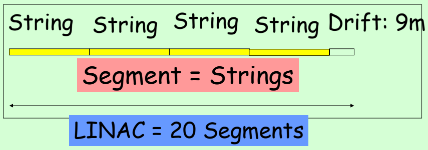
1 Quadrupole per 3 Cryo Modules = RF Unit (35 m)

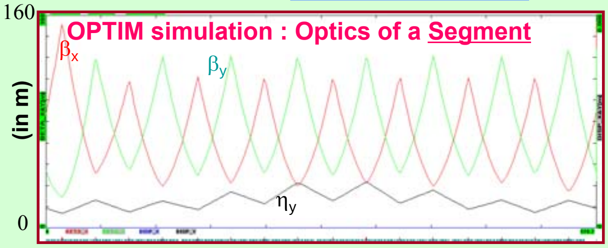



Cold drift of 2 m at the end of a String (142 m)

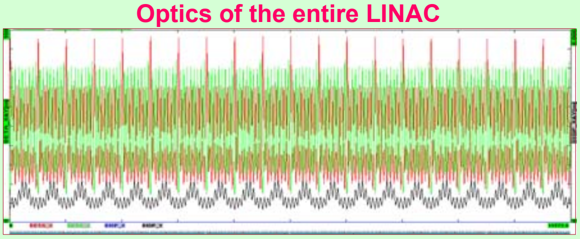


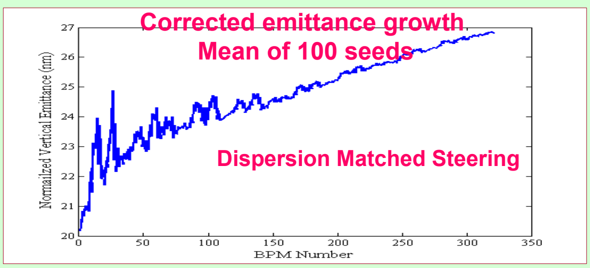

Warm diagnostics section of 9 m at the end of a Segment (578 m)




Optics of the entire LINAC



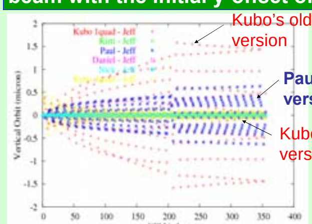



# 3. CROSS-CHECKING CODES

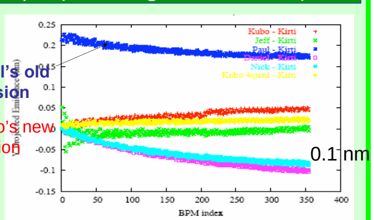
Different codes used for emittance preservation - BMAD (TAO), PLACET, MERLIN, SLEPT, MATLIAR, CHEF –exercise #1

- compared by different people at CERN, DESY, Cornell, KEK, SLAC and FERMILAB

➢ EX# 1: In perfectly aligned LINAC (TESLA lattice), launch the beam with the initial y-offset of 5 $\mu$m (including TESLA wakes)

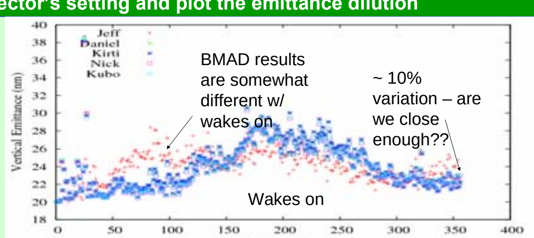



Difference in the vertical orbit at the BPMs w.r.t. BMAD




Difference in PROJECTED VERTICAL EMITTANCE w.r.t. MATLIAR

➢ PT (SLAC) generated the Misalignments file (for Quads, BPMs and cavities) using MATLIAR and also the vertical corrector's setting for the DFS EX # 2: Include the misalignments and the vertical corrector's setting and plot the emittance dilution

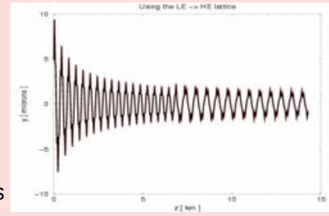



# 4. Low Emittance Transport Tools Development

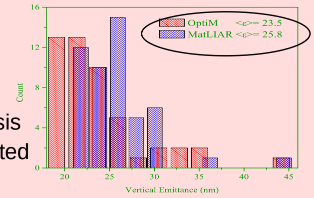
- **CHEF** ***(by Leo Michelotti & Francois Ostiguy, FNAL )***
  - –Interactive program for accelerator Optics
  - –Uses high level graphical user interfaces to facilitate the exploitation of lower level tools incorporated into a hierarchy of C++ class libraries.
  - –GUI integrated, Linux, Windows
  - –Used for circular machines and transfer lines,

  ***now upgrading for ILC studies***

Y-orbit comparison b/w MERLIN and CHEF for 5 $\mu$m initial y-offset (exercise # 1)

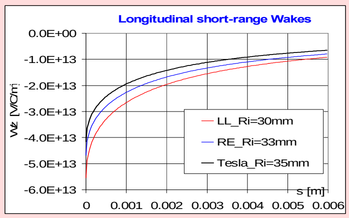


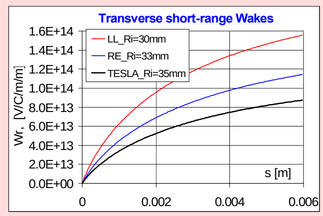

- **OptiM** ***(by V. Lebedev, FNAL )***
  - – Used for more than 10 years
  - – Integrated system for Optics design, support and measurement analysis
  - – Similar to MAD but with integrated GUI
  - – Wake fields, tracking
  - – No beam based alignment features yet



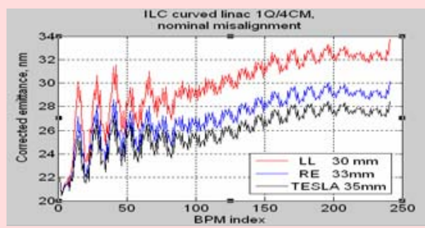

Emittance dilution in **MatLIAR** and **OptiM** with 1$\mu$m Quad misalignments in Curved ILC Linac

# 5. WAKEFIELD CALCULATIONS



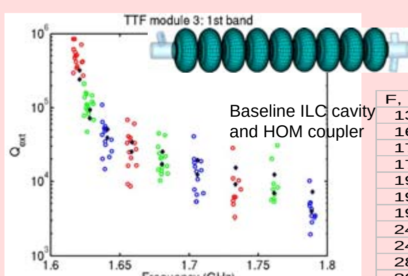

**Corrected Emittance Dilution vs. BPM index for different wakefields**




# 6. HOM STUDIES

➢ Preliminary results of Multi-bunch emittance preservation indicate that the effect of random frequency errors down the complete linacis extremely beneficial! However, attention must also be paid to modes trapped in cavity. These can lead to a large emittance dilution! (R. Jones)

➢ What we are doing:
- R/Q and $Q_{ext}$ for a few first pass bands in real solid model
- $Q_{ext}$ scattering due to cavity imperfections and inter-cavity spacing
- Optimization (new design) of HOM coupler

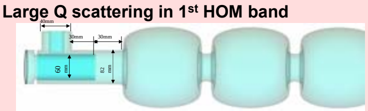



Baseline ILC cavity and HOM coupler

| F, MHz | Qext | Rsh/Q | mode |
|---|---|---|---|
| 1300 | 8.00E+05 | | M1 |
| 1696 | 1.65E+03 | 22968 | D1 |
| 1721 | 2.88E+03 | 93247 | D1 |
| 1747 | 5.59E+03 | 32916 | D1 |
| 1902 | 1.76E+04 | 72992 | D2 |
| 1917 | 2.77E+04 | 158985 | D2 |
| 1931 | 4.60E+04 | 89321 | D2 |
| 2420 | 1.03E+05 | 180097 | D3 |
| 2424 | 1.96E+04 | 202969 | D3 |
| 2829 | 1.99E+04 | 8000 | D4 |
| 3072 | 1.74E+04 | 8266 | D5 |
| 3335 | 1.42E+05 | 15618 | D6 |

**Measured $Q_{ext}$ in 8 cavities(CM#3).**

**Large Q scattering in 1st HOM band**



**Alternative design for cavity, HOM and Main Coupler (coaxial coupling to cavity) provide good HOM damping**